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Combined while-drilling techniques for the assessment of deteriorated concrete cover

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Abstract

In this paper the idea of monitoring the resistance encountered while taking a sample from a concrete structure and to combine this data with the analysis of the extracted material has been regarded as a method for detecting the possible deterioration of the concrete cover. In the common case of core drilling, the time spent for a unit penetration proved to be a good indicator of the local material response. Hence, the laboratory analyses can be easily integrated with this preliminary scan of the material quality, which comes at no cost once the acquisition of samples has been planned. On the other hand, hammer-drilling of small holes is a definitely faster and less invasive alternative for inspecting the mechanical response at increasing depth within the cover. Although this method is not intended to provide a material sample, the analysis of the ground-concrete powder and the visual inspection of the remaining hole proved to be a viable alternative to the traditional examination of cores.

Résumé

Le monitoring de la résistance du béton pendant l'extraction d'un échantillon et la combinaison de ces informations avec les résultats de l'analyse physico-chimie et mécanique du matériel est considérée de plus en plus comme une méthode efficace pour l'identification de toute détérioration dans le recouvrement en béton. Lorsqu'on perce une carotte, la durée nécessaire pour une pénétration unitaire est un indicateur fiable de la réponse du matériau. Donc, on peut facilement intégrer les analyses de laboratoire avec les indications préliminaires sur la qualité du matériau, qui viennent gratuitement, en complément, à condition d'avoir planifié l'acquisition des échantillons. Par contre, le perçage par une perceuse à percussion dotée d'une foret de petit diamètre est un moyen alternatif nettement plus rapide et moins envahissant pour avoir des renseignements sur la réponse mécanique du béton de recouvrement, à différentes profondeurs. Bien que la perceuse ne permette pas d'obtenir des échantillons, l'analyse de la poussière de béton et l'inspection visuelle du trou est souvent une alternative utilisable par rapport aux traditionnels essais sur carottes.

Keywords

Carbonation, colour, core, endoscope, thermal analysis.

1 Introduction

Most of the external agents having an effect on the durability of concrete structures (freeze and thaw, fire, carbonation, alkali-silica reaction, etc) lead to more or less pronounced variations of the material properties within the concrete cover. The assessment of such gradients cannot be easily performed via the commonly available ND techniques, whose objective is generally to smooth the effect of the inherent heterogeneities of the material at the scale of the coarse aggregate, which is also the significant range of the problem at issue.

Despite of the possible detriment to the integrity of the structure, a common approach to this problem is based on the extraction of cores, to be examined as they are (visual observation, colour measurement, ultrasonic scan) or to be cut into slices for subsequent laboratory analyses, as in the case of fire damage assessment [1-4]. A number of investigation techniques are available to this latter purpose, involving the mechanical response of each slice (splitting, punching-load compression, dynamic Young's modulus), their physical and morphological features (colour, micro-crack density, porosity, air permeability, petrographic and SEM examinations) and their physicochemical properties (X-ray diffraction, thermal and chemical analyses). The results pertaining to each slice can then be sorted into a profile depicting the evolution within the concrete cover of the property under study.

This wide assortment of inspection techniques paves the way for the implementation of combined methods, in which an improved accuracy is achieved by properly merging different sets of results. In this perspective, the operation of coring a concrete member can be itself considered as a way of scanning the material soundness at increasing depth, which comes at no cost after having decided to take samples of the deteriorated concrete.

To date, the potential of monitoring the core cutting process, that is a well established practice in geophysical prospection, has not been studied systematically for the assessment of construction materials. On the contrary, several examples of this kind of approach applied to the simple drilling of holes are available in the literature. By means of suitably modified drills, different operational parameters can be surveyed, like the thrust or the torque to be exerted to keep a constant feed rate [5] and the mechanical work spent for a unit penetration of the bit [6]. The attractive pros of this technique are the little time required to run a test, the immediate availability of the results and the limited damage to the member under consideration. Compared to the core extraction, the main limitation is the lack of a material sample to be submitted to further analyses, though the remaining hole and the ensuing ground-concrete powder could be in principle the object of additional investigations.

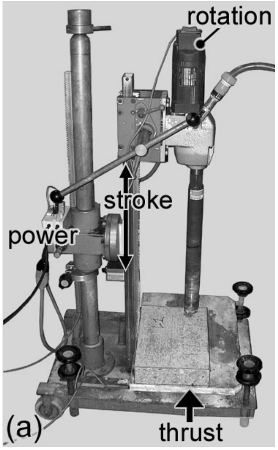
In this paper a comparison among some drilling and coring resistance indicators is performed first, in order to ascertain the sensitivity of these methods to a steep gradient of the mechanical properties. Then the potentials of the visual observation of the drilled hole and the analysis of the ensuing powder are checked, as a way to implement the combination of different assessment techniques even in the absence of an undisturbed concrete sample.

2 Coring and drilling resistance

In order to monitor the process of cutting a concrete core, a common core drill has been fitted with a set of sensors for measuring the rotational speed, the longitudinal stroke, the exerted thrust and the electric power consumption (Fig. 1a). The most significant parameters that can be worked out for revealing the quality of the material are the specific work (J/mm^3 - work per unit notched volume) and the time spent for a unit advance of the tool (s/mm).

In a first series of tests, the effect of the working variables (bit diameter, exerted thrust, rotation rate) has been studied by coring some ordinary concrete cubes (side = 150 mm, average cubic strength R_{cm} = 50 N/mm^2 - Fig. 2). At the reference rotational speed (600 rpm), the results show a relatively stable specific work consumption for increasing tool size and thrust (Fig. 2), whereas a concurrent reduction of the drilling time and rise of the electrical power input are observed. The same trends have been recognized by increasing the rotational speed (1250 rpm, not reported here). The slower rotation and the intermediate thrust (1.36 N/mm^2) have been adopted in the following series of tests, together with the smallest core bit ($Ø_{int}$ = 44 mm), which has the advantage of a minor damage to the investigated member.

The sensitivity of the two cited coring resistance indicators to the mechanical weakening of a deteriorated material has been ascertained on two sets of cubes, made of an ordinary and a lightweight concrete (average cubic strength R_{cm} = 50 N/mm^2 - max aggregate size = 16 mm). The samples have been tested as they were or after being uniformly damaged by way of a slow thermal cycle (T_{max} = 200÷800°C, heating/cooling rates = 0.5/0.2°C/min, 1 hour spell at T_{max}). Identical samples were used also in other studies in order to compare the effectiveness of a series of ND techniques [1, 7]. Among them, a like method based on the measurement of



core bits geometry

#	Ø$_{int}$ (mm)	thick (mm)	area (mm^2)
1	44	3.5	522
2	54	3.8	680
3	64	3.5	748
4	74	3.5	852
5	100	3.5	1138

exerted thrust

#	thrust (N/mm^2)
a	0.69
b	1.36
c	2.05

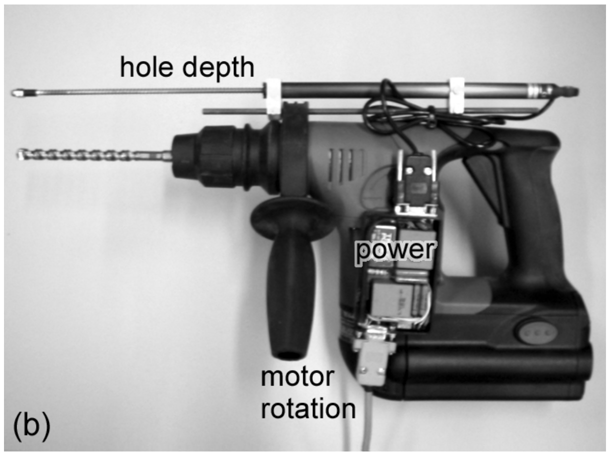


Figure 1. *(a) The core drill fitted with the sensors for monitoring the operational parameters and variables investigated in the preliminary tests; (b) modified hammer-drill for measuring the drilling resistance [6].*

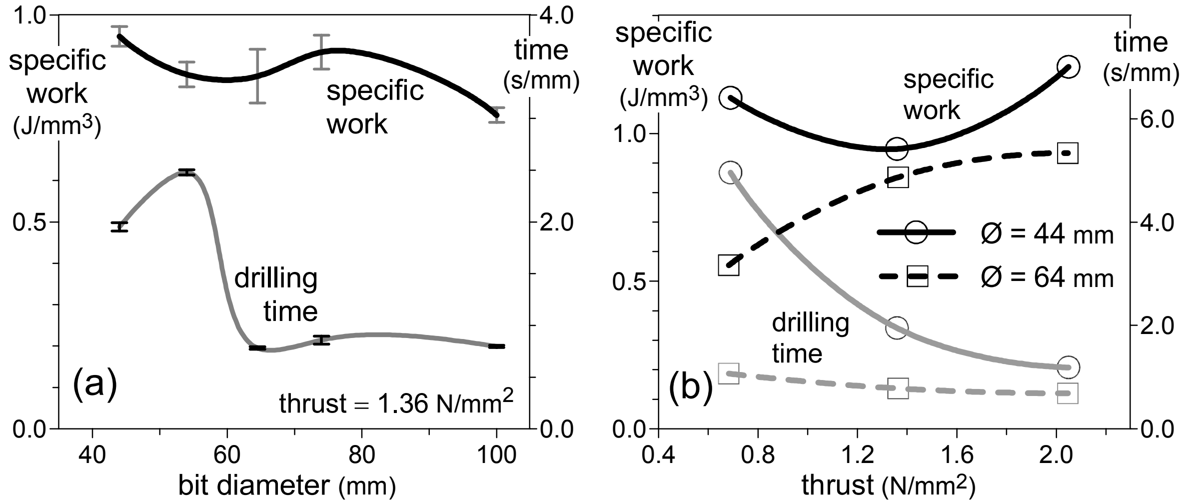


Figure 2. *Results of the preliminary core drilling tests under varying bit diameter and exerted thrust (rotational speed 600 rpm).*

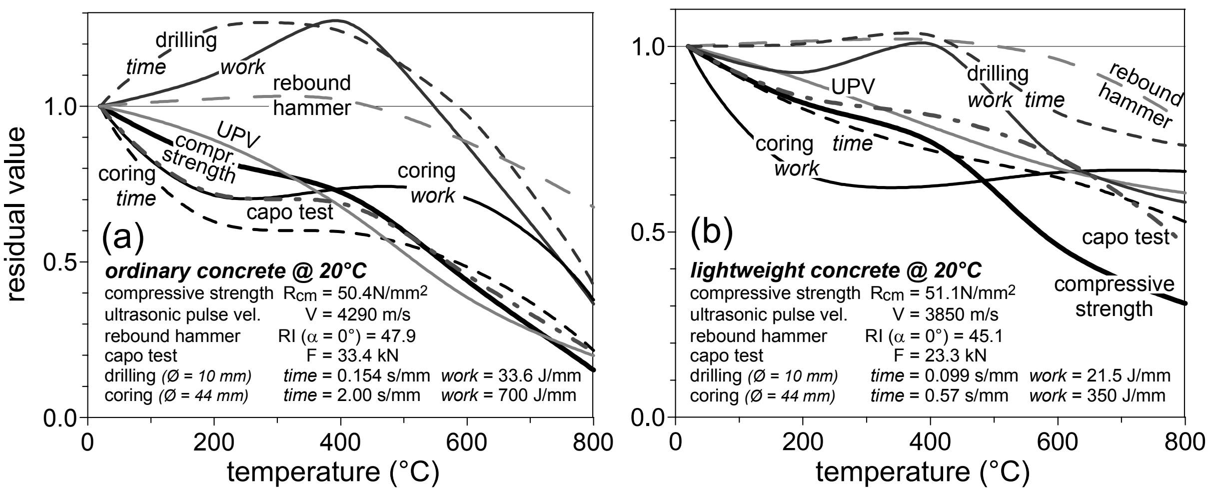


Figure 3. *Sensitivity to a uniform thermal damage of some common ND techniques and of the two drilling methods herein investigated.*

the drilling resistance via a modified hammer-drill has been also thoroughly deepened (Fig. 1b [6]). A summary of all the results is presented in Fig. 3.

In principle the coring and the hammer-drilling techniques are based on the same micro-fracturing mechanism induced by a hard indenter scratching the concrete surface. However, the diamond-tipped bit of the core drill is fitted with a number of small hard grains, which have the effect of finely milling the material. On the contrary, the bit of a hammer-drill ends with a single large indenter submitted to strong pressure pulses, leading to a deeper propagation of cracks and a coarser fragmentation, especially in stiff and brittle materials like rock and high grade concrete. Hammer-drilling is then far less energy demanding than coring, but a rise of both the drilling work and time can be observed in slightly damaged concretes, when the increased deformability and almost constant fracture energy give way to less efficient penetration mechanisms (plastic crushing and milling rather than chipping [6]).

For this reason, even being the most promising parameter to be monitored in hammer-drilling, the dissipated work proved to be not enough sensitive to low levels of damage. On the other hand, the elapsed time is the most responsive parameter in core drilling, provided that a careful control of the exerted thrust is performed. The fairly good sensitivity to thermal damage of this latter value can be compared to some well established ND techniques (ultrasonic pulse velocity and capo test) and to the compressive strength itself.

The interesting feature of both the discussed drilling techniques is their ability to continuously scan the material response at increasing depth, even in presence of strong gradients due to the concrete cover deterioration. As an example, Fig. 4 reports the profiles recorded while drilling a ordinary-concrete panel (thickness = 80 mm) that was preliminarily exposed to a steep thermal gradient (675 to 230°C left to right [7]). Based on the maximum temperatures reached in the panel and on the calibration curves of Fig. 3a, the expected drilling resistance profiles have been also worked out for reference. The general good agreement with the measured profiles confirms the reliability of this approach. Other features to be noted are the lower initial resistance due to the settlement of the cutting-tools, the remarkable sensitivity of the core drilling time to low damage levels (a 30% decay compared to unheated concrete is recognized already on the cold side of the panel) and the higher influence of the hard aggregate pebbles on the hammer drilling results, which requires to average some tests in order to recognize a clear trend. In the common case of shallow degradation of relatively thick members, a steady resistance value is reached in the end of the drilling process, when the pristine material is inspected. This allows to plot the profiles in relative terms, releasing from the need of specific calibration curves for a first assessment of the damaged depth.

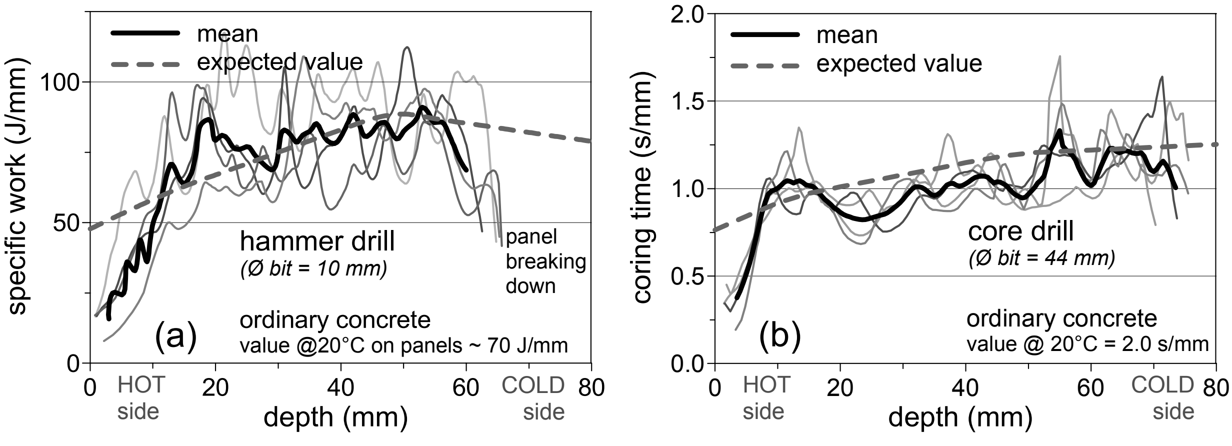


Figure 4. *Profiles of the most significant drilling and coring resistance indicators in the case of a concrete panel exposed to a steep thermal gradient.*

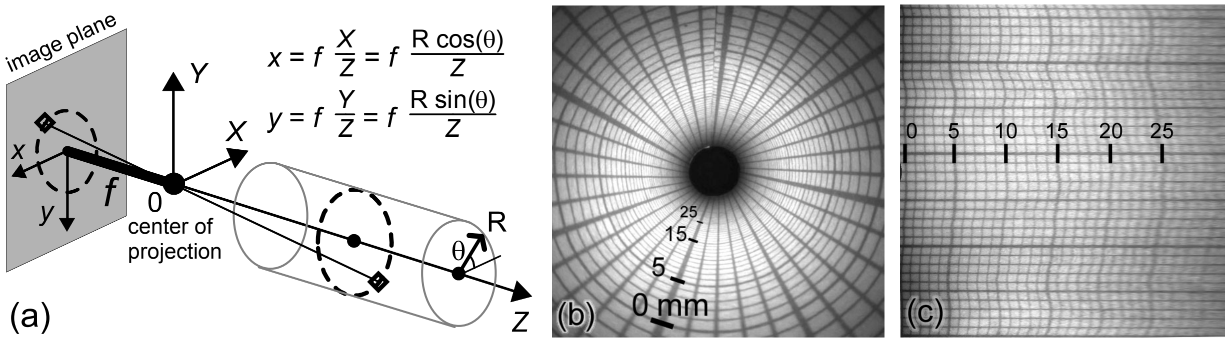


Figure 5. *(a) Endoscopic image projection on the CCD sensor of the digital camera; (b) original and (c) unwrapped views of a rolled graph paper.*

3 Visual inspection of the drilled holes

One advantage of taking a core from a member, compared to hammer-drilling, is the opportunity to observe the extracted samples for ascertaining the material morphology and condition. Nonetheless, the point of view can be reversed by examining the drilled holes through an optical endoscope. The limitation of this instrument is to provide a magnified view of a just a small portion of the cavity, making difficult to gather a complete representation of the inner surface and to preserve the geometrical proportion of the observed details. A number of techniques have been proposed for the calibration, projection and merging of the endoscope images, mainly aimed at medical and surgical applications.

In this study a rather simple approach has been implemented so to allow a first check on the viability and significance of this kind of observation. A rigid endoscope with frontal view and a wide field of vision (100 deg) has been fitted with a digital USB camera, in order to store a series of digital images at regular 10 mm steps. The images are processed in order to switch from the central perspective to a front view of the unwrapped cylindrical surface of the hole. The transformation is based on the pinhole-model of the image projection on the CCD sensor of the camera (Fig. 5 [8]). By assuming a fixed radius of the hole ($R = 5$ mm in this case) and a perfect alignment of the endoscope axis, a simple relationship can be established between the coordinates of the cylindrical surface and the pixels on the image plane. The unwrapped frames are then merged by means of a software for image editing.

The comparison between the internal image of one hole drilled in a heated concrete panel (Fig. 6a) and the side view of a core taken from the same sample (Fig. 6b) allows to point out the limitations and the potential of this technique. As expected, the limited size of the drilled hole doesn't allow to recognize the material texture nor the shape and nature of the coarse aggregate. Moreover, the significant roughness of the hole produced by hammer-drilling makes the visual recognition of small pores and flaws quite a difficult task.

Nevertheless, some averaged values can still be measured, like the slight discoloration occurring along the hole axis. In a former study, the analysis of the digital images of concrete samples has been regarded as a method for detecting the colour variations induced by the exposure of concrete to high temperature [9]. This technique can be implemented on both kinds of image, though a change of the illuminant generally produces a shift of the chromaticity diagrams (a halogen source and the natural daylight have been used in the two images at issue). However, being significant the colour variation compared to pristine concrete, this bias can be deleted by zeroing the plots in the range pertaining to the undamaged material. It can be observed that the two images provide comparable trends of the pink discoloration which generally affects heated concrete in the range 300-600°C (Fig. 6c). A greater noise characterizes the plot obtained from the drilled hole, which is also more sensitive to the return to whitish-grey taking place at higher temperatures.

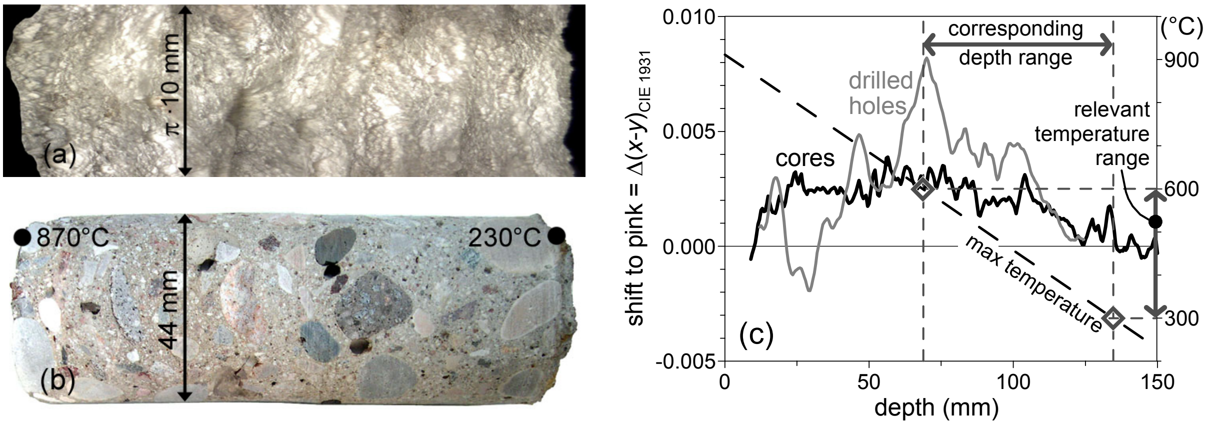


Figure 6. *View of (a) them unwrapped inner surface of a drilled hole and (b) a core taken from the same concrete panel submitted to a thermal gradient; (c) colour alteration profiles within the panel determined via xthe digital image analysis.*

4 Analysis of drilling-powder samples

Several physicochemical analyses on concrete require a preliminary grinding of the material into a fine powder (X-ray diffraction, chloride-ions content, Differential Thermal Analysis, Thermo-Gravimetric Analysis, etc). Moreover, some tests that are normally performed on the intact samples, may be in principle carried out also on the material in pulverized form (carbonation depth, colour measurement, etc).

This evidence casts the base for merging the results of the hammer-drill perforation test and the following examination of the ensuing powder. Compared to the ordinary laboratory practice, the only limitation is the impracticality of controlling whether to include or not the coarse aggregate in the sample. In case of steep variations of the investigated properties with the drilling depth, an important requirement is to preserve the order of extraction, so to obtain a sorted sample of powder. A special device has been developed to this purpose.

In order to check the viability of this kind of test, different types of analysis have been performed on sorted samples of powder obtained by drilling concrete with a 10 mm diameter bit. The first example concerns the determination of the carbonation depth through the application of a pH indicator to the freshly powdered concrete (Fig. 7a). This method provides practically the same results as the traditional analysis of micro-cores, with the advantage of smoothing the local irregularities of the carbonation front (Fig. 7b), making easier the interpretation of the test result. The adoption of a transparent test tube allows also to detect the slight concrete colour variations induced by the exposure to high temperature, as already discussed in the previous section (see the analogy between Fig. 7c and Fig. 6b).

The last example regards the differential thermal analysis (DTA), that involves the heating a small sample of powdered concrete together with a similar amount of inert material (e.g. aluminium oxide Al_2O_3). Both samples are monitored in order to trace their temperature difference, which ensues from the transformations occurring in the tested material. This method has been proposed as a way for analyzing fire damaged concrete, because during this second heating minor or different transformations occur until the maximum temperature experienced during the fire is exceeded [10]. In the case a temperature profile through the cover has to be worked out, the DT analysis has to be repeated on a series of samples taken at increasing depth, which is quite a demanding procedure.

In order to overcome this limitation, a sorted sample of drilling-powder has been collected in a metal pipe, together with a small amount of aluminium oxide. The pipe (Fig. 8a) is made of a thermally stable alloy (nickel-chromium) and it is perforated at regular steps along one generatrix so to allow to vent the developing gases and to embed a series of thin shielded

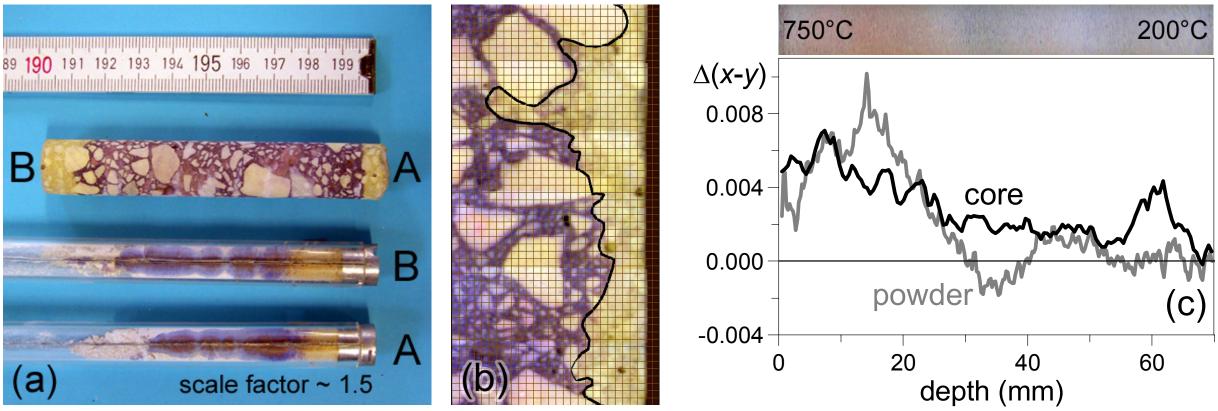


Figure 7. *(a) Carbonation depth in a 100 mm concrete cube determined on a micro-core and on two sorted samples of powder; (b) local irregularities of the carbonation front and c) discoloration of the powder sample taken from a heated panel.*

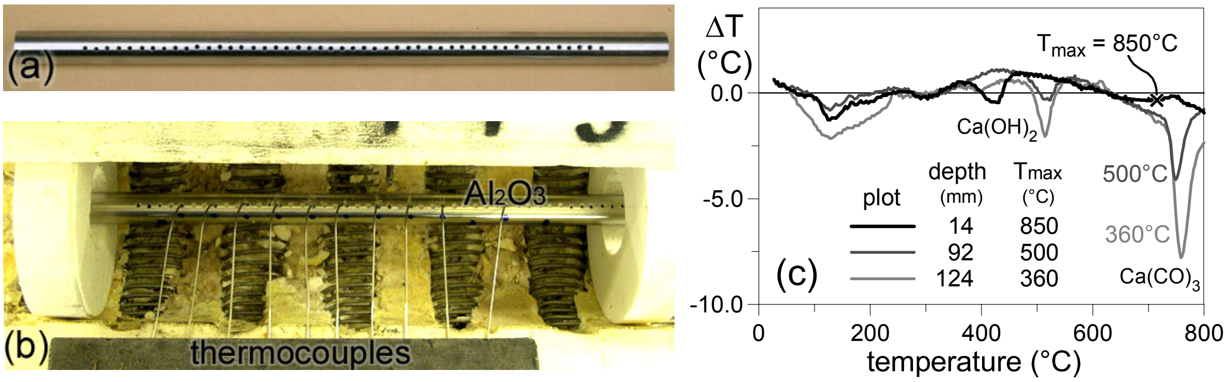


Figure 8. *(a) Nickel-chromium perforated pipe to be filled with a sorted sample of drilling-powder and (b) test setup in the split-tube furnace; (c) temperature differentials pertaining to different depths in a heated panel (see Fig. 6).*

thermocouples in the inner powder (Fig. 8b). By heating the pipe in a split-tube furnace (5°C/min) several DT analyses can be performed in one take. Though less rigorous than adopting the standard test procedure and a dedicated device, this method is far less time demanding and still allows to detect the onset of the relevant transformations. The first results (Fig. 8c) pertaining to the same panel already mentioned in Fig. 6 seem in good agreement with the trends reported in the literature [10]. The anticipated dissociation of the calcium-hydroxide resulting from the calcium-oxide rehydration compared to unheated portlandite (350-500°C) and the disappearance of the peak ascribable to the calcium-carbonate dissociation (700-800°C) are the main features to trace on the thermo-differential plots.

5 Conclusions

In this paper the idea to monitor the resistance encountered while drilling a concrete member and then to analyse the ensuing material has been regarded as a combined method for detecting the possible deterioration of the concrete cover. In this perspective, the well established practice of analysing the drilled cores can take advantage of this preliminary scan of the material response, which comes at no cost once the acquisition of samples has been planned. On the other hand, the faster and less invasive monitoring of the hammer-drilling resistance, that in principle is not intended to provide any material sample, can be fostered by the analysis of both the ensuing ground-concrete powder and the remaining hole. The results obtained in these different directions can be summarized as follows.

The penetration rate of the core bit, at constant exerted thrust, is the most responsive parameter to be monitored while drilling a concrete member. The sensitivity is comparable to other effective ND techniques, with the additional benefit of a point-by-point analysis at increasing depth. As concerns the hammer-drilling technique, the energy spent to penetrate the material is the most significant parameter to be surveyed, with the limitation of a poor sensitivity to low levels of material damage.

A valuable support to the visual inspection of the drilled holes is the proper processing of the endoscopic images, aimed to provide a front view of the unwrapped cylindrical surface of the cavity. However, the limited size and the considerable roughness characterizing the holes produced by hammer-drilling make the recognition of the material texture and the detection of any small flaws quite a difficult task. On the contrary, the analysis of more sketchy features, like the discolouration due to either the material alteration or the application of chemical indicators, may still compete with the traditional inspection of cores.

Collecting the powder produced while drilling a member is a convenient alternative to cores in case the laboratory analyses require a preliminary grounding of concrete into a fine powder. The tests concerning the carbonation depth, the colour alterations and the physicochemical response of the material seem to confirm the viability of this method. The only drawback is the impracticality of controlling the effect of the coarse aggregate, whose local influence may prevail in relatively small drilled holes.

These results are intended as a first check on the viability and significance of the testing techniques herein proposed. A systematic study on their reliability will be necessary in order to factually merge different test results in the assessment of the deteriorated concrete cover.

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